

**APPLICATION**

**FOR**

**UNITED STATES LETTERS PATENT**

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**SPECIFICATION**

1 TO ALL WHOM IT MAY CONCERN:

2 Be it known that I, William L. Puskas, a citizen of the United States of America, have  
3 invented

4 **Apparatus and Methods for Cleaning and/or Processing Delicate Parts**

5 of which the following is a specification.

1   **Apparatus and Methods for Cleaning and/or Processing Delicate Parts**

2  
3   Related Applications

4  
5       This application is a continuation-in-part of Provisional Application No.  
6   60/023,150, filed on August 5, 1996, and entitled "Apparatus and Methods for Processing  
7   and Cleaning Semiconductor Wafers and Other Delicate Parts."

8  
9   Field of the Invention

10  
11       The invention relates to systems and methods for cleaning and/or processing delicate  
12   parts, e.g., semiconductor wafers. In particular, the invention relates to ultrasonic systems,  
13   ultrasonic generators, ultrasonic transducers, and methods which support or enhance the  
14   application of ultrasonic energy within liquid.

15  
16   Background of the Invention

17  
18       Ultrasonic energy has many uses; and applications of ultrasound are widespread in  
19   medicine, in the military industrial complex, and in engineering. One use of ultrasound in  
20   modern manufacturing and processing is to process and/or clean objects within liquids. For  
21   example, it is well-known that objects within an aqueous solution such as water can be  
22   cleaned by applying ultrasonic energy to the water. Typical ultrasound transducers are, for  
23   example, made from materials such as piezoelectrics, ceramics, or magnetostrictives  
24   (aluminum and iron alloys or nickel and iron alloys) which oscillate with the frequency of the  
25   applied voltage or current. These transducers transmit ultrasound into a tank filled with liquid  
26   that also covers some or all of the object to be cleaned or processed. By driving the  
27   transducer at its operational resonant frequency, e.g., 18khz, 25khz, 40khz, 670khz or 1Mhz,  
28   the transducer imparts ultrasonic energy to the liquid and, hence, to the object. The

1 interaction between the energized liquid and the object create the desired cleaning or  
2 processing action.

3  
4 By way of example, in the 1970s ultrasonic energy was used in liquid processing  
5 tanks and liquid cleaning tanks to enhance the manufacture of semiconductor devices and  
6 other delicate items. The typical ultrasonic frequency of such processes was a single  
7 frequency between 25khz to 50khz. Many prior art generators exist which produce single  
8 frequency ultrasonics, including those described in U.S. Patent Nos. 3,152,295; 3,293,456;  
9 3,629,726; 3,638,087; 3,648,188; 3,651,352; 3,727,112; 3,842,340; 4,044,297; 4,054,848;  
10 4,069,444; 4,081,706; 4,109,174; 4,141,608; 4,156,157; 4,175,242; 4,275,363; and  
11 4,418,297.

12  
13 The early ultrasonic transducers were typically piezoelectric ceramics that were  
14 "clamped," i.e., compressed, so as to operate at their fundamental resonant or anti-resonant  
15 frequency. Many prior art clamped transducers exist, including those found in U.S. Patent  
16 Nos. 3,066,232; 3,094,314; 3,113,761; 3,187,207; 3,230,403; 3,778,758; 3,804,329 and RE  
17 25,433. Other ultrasound transducers are made of alloys that possess magnetostriction  
18 properties which cause them to expand or contract under the influence of a magnetic field.

19  
20 As mentioned above, these transducers were bonded to or placed in tanks which  
21 housed the cleaning or processing liquid. Typically, such tanks were constructed of a material  
22 compatible with the processing liquid, such as: 316L stainless steel for most aqueous  
23 chemistries; 304 stainless steel for many solvents; plastics such as Teflon, polypropylene, and  
24 metals such as tantalum for strong acids; and coated metals such as Teflon-coated stainless  
25 steel for corrosive liquids.

26  
27 In order to deliver ultrasound to the solution within the tank, the transducers were  
28 attached to, or made integral with, the tank. In one method, for example, epoxy bonds or  
29 brazing were used to attach the transducers to tanks made of metallic stainless steel, tantalum,

1 titanium, or Hastalloy. In another prior art method, the drive elements of the transducers  
2 were machined or cast into the tank material, and the piezoelectric ceramic and backplates  
3 were assembled to the drive elements.

4  
5 The prior art also provides systems which utilize ultrasonic transducers in conjunction  
6 with plastic tanks. Typically, the tank's plastic surface was etched to create a surface that  
7 facilitated an epoxy bond thereon. The transducers were bonded with epoxy to the etched  
8 surface, and various techniques were used to keep the system cool to protect the plastic from  
9 deterioration. One such technique was to bond the transducers to an aluminum plate that  
10 would act as a heat-sink, and then to bond the aluminum plate to the plastic surface. Often,  
11 fans would be directed toward the aluminum plate and the transducers so as to enhance  
12 cooling. Another cooling technique utilized a thin plastic, or a process of machining the  
13 plastic at the transducer bonding position, to provide a thin wall at the transducer mounting  
14 position. This technique enhanced the cooling of the plastic and transducer by improved heat  
15 conduction into the liquid, and further improved the coupling of sound into the processing  
16 liquid because of less sound absorption.

17  
18 With advances in plastic formulations such as PEEK (polyetheretherketone), the prior  
19 art made improvements to the plastic ultrasonic tank by further reducing the sound absorption  
20 within the plastic material. The prior art further developed techniques for molding the  
21 transducers into the plastic material, such as through injection and rotational molding, which  
22 further improved the manufacturing of the tank as well as the processing characteristics  
23 within the tank.

24  
25 For other materials such as ceramics, glass, Pyrex and quartz, the prior art used epoxy  
26 to bond the transducer to the tank surface. Casting the transducer into the material was also  
27 possible, but was not commercially used. Often, the radiating surface (i.e., the surface(s)  
28 with the ultrasonic transducers mounted thereon or therein), usually the tank bottom, would  
29 be pitched by at least one-quarter wavelength to upset standing wave patterns within the

1 tank. Other tank configurations which provided similar advantages are reported in the prior  
2 art, such as disclosed by Javorik in U.S. Patent No. 4,836,684.

3  
4 An alternative to bonding the transducer directly to the bottom or sides of the tank  
5 was developed in the prior art by bonding the transducer to a window or plate that was sealed  
6 within a tank opening via a gasket. This had several advantages. If the transducer failed, or  
7 if cavitation erosion occurred within the radiating surface, the window or plate could be  
8 replaced without the expense of replacing the whole tank. Another advantage was the ability  
9 to use dissimilar materials. For example, a quartz tank with a tantalum window offered the  
10 advantage of an acid resistant material for the tank, and a metallic bonding and radiating  
11 surface for the transducer. In U.S. Patent No. 4,118,649, Schwartzman described the use of a  
12 tantalum window with bonded transducers which coupled ultrasonic energy into a  
13 semiconductor wafer process tank.

14  
15 A second alternative to direct bonding between the transducers and the tank was  
16 developed, in the prior art, by bonding the transducers inside a sealed container, called an  
17 "immersible" or "submersible," which was placed under the liquid in the process or cleaning  
18 tank. Certain advantages were also presented in this method, including (a) the relatively  
19 inexpensive replacement of the container, and (b) the use of dissimilar materials, described  
20 above. In U.S. Patent No. 3,318,578, Branson discloses one such immersible where both the  
21 transducers and the generator are sealed in the container.

22  
23 There are, however, certain disadvantages associated with above-described  
24 alternatives to direct bonding between the transducers and the tank. One such disadvantage is  
25 the occasional entrapment of contamination within the area of the window, or the window  
26 gasket, or under the immersible. When contamination-free processing is required, a direct  
27 bonded coved corner tank provides a better solution.

1           Although tanks, plates, windows and immersibles usually had clamped transducers  
2 bonded thereon, the prior art sometimes utilized an unclamped piezoelectric shape or an array  
3 of unclamped piezoelectric shapes, such as PZT-4 or PZT-8, which were bonded directly to  
4 the tank, plate, window or immersible. By way of example, U.S. Patent No. 4,118,649  
5 describes transducers shaped into hexagons, rectangles, circles, and squares and bonded to a  
6 window. These unclamped transducers had the advantage of lower cost. They further could  
7 be operated in either the radial mode, for low frequency resonance, or in the longitudinal  
8 mode for "megasonic" frequency resonance (i.e., "megasonic" frequencies generally  
9 correspond to those frequencies between about 600khz and 2Mhz).

10  
11           Nevertheless, these prior art unclamped transducers proved to be less reliable as  
12 compared to prior art clamped transducers. Accordingly, these shaped transducer arrays were  
13 used primarily in low-cost bench-top ultrasonic baths, or in megasonic equipment where high  
14 frequency ultrasonic resonance was utilized. Still, these transducers proved to be particularly  
15 unreliable when operating at megasonic frequencies because of the high frequency stress  
16 affecting the ceramics.

17  
18           One other system in the prior art used to couple acoustics into a liquid is commonly  
19 referred to as a "double boiler" system. In the double boiler system, an ultrasonic plate, tank,  
20 window or immersible transmits the ultrasonics into a coupling liquid. A processing tank,  
21 beaker or other container containing the processing or cleaning chemistry is then immersed  
22 into the coupling liquid. Accordingly, the ultrasound generated within the coupling liquid  
23 transmits into the tank containing the processing or cleaning liquid. The double boiler system  
24 has several advantages. One advantage is in material selection: the transducer support  
25 structure can be made out of an inexpensive material, such as stainless steel; the coupling  
26 liquid can be a relatively inert substance, such as DI water; and the process tank can be a  
27 material such as quartz or plastic material, which fares well with an aggressive chemistry  
28 such as sulfuric acid. Another advantage is that one transducer driving a relatively inert  
29 coupling liquid can deliver ultrasound into several different processing tanks, each containing

1 different chemistries. Other advantages of the double boiler system are that the coupling  
2 fluid can be chosen so that its threshold of cavitation is above the cavitation threshold of the  
3 processing chemistry; and the depth of the coupling liquid can be adjusted for maximum  
4 transmission efficiency into the process tank(s). U.S. Patent No. 4,543,130 discloses one  
5 double boiler system where sound is transmitted into an inert liquid, through a quartz  
6 window, and into the semiconductor cleaning liquid.

7  
8 The prior art also recognizes multi-functional, single chamber ultrasonic process  
9 systems which deliver ultrasonic cleaning or processing to liquids. In such systems, the  
10 cleaning, rinsing, and drying are done in the same tank. Pedziwiatr discloses one such system  
11 in U.S. Patent No. 4,409,999, where a single ultrasonic cleaning tank is alternately filled and  
12 drained with cleaning solution and rinsing solution, and is thereafter supplied with drying air.  
13 Other examples of single- chamber ultrasonic process systems are disclosed in U.S. Patent  
14 Nos. 3,690,333; 5,143,103; 5,201,958, and German Patent No. 29 50 893.

15  
16 In the prior art, "directed field tanks" are sometimes employed where the parts to be  
17 processed have fairly significant absorption at ultrasonic frequencies. More particularly, a  
18 directed field tank has transducers mounted on several sides of the tank, where each side is  
19 angled such that ultrasound is directed toward the center of the tank from the several sides.  
20 This technique is useful, for example, in supplying ultrasound to the center of a filled wafer  
21 boat.

22  
23 In the late 1980s, as semiconductor device geometries became smaller, and as  
24 densities became higher, many shortcomings were discovered with respect to conventional  
25 low-frequency ultrasonic processing and cleaning of semiconductor wafers. The main  
26 disadvantage was that the existing ultrasound systems damaged the parts, and reduced  
27 production yields. In particular, such systems typically generated a sound wave with a single  
28 frequency, or with a very narrow band of frequencies. In many cases, the single frequency,  
29 or narrow band of frequencies, would change as a function of the temperature and age of the

transducers. In any event, the prior art ultrasonic systems sometimes generated sufficient cycles of sound within a narrow bandwidth so as to excite or resonate a mode of the processed part. The relatively large displacement amplitudes that exist during such a mode resonance would often damage the delicate part.

Another disadvantage of single frequency ultrasound (or narrow band ultrasound) is the standing waves created by the resonances within the liquid. The pressure anti-nodes in this standing wave are regions of intense cavitation and the pressure nodes are regions of little activity. Therefore, undesirable and non-uniform processing occurs in a standing wave sound field.

In addition to the resonant and standing wave damages caused by single frequency ultrasound (or narrow band ultrasound), damages are also caused by (a) the energy levels of each cavitation implosion, and (b) by lower frequency resonances, each of which is discussed below.

The prior art methods for eliminating or reducing the damage caused by the energy in each cavitation implosion are well known. The energy in each cavitation implosion decreases as the temperature of the liquid is increased, as the pressure on the liquid is decreased, as the surface tension of the liquid is decreased, and as the frequency of the sound is increased. Any one or combination of these methods are used to decrease the energy in each cavitation implosion.

By way of example, one benefit in reducing the energy in each cavitation implosion is realized in the manufacture of hard disk drives for computers. The base media for a hard disk is an aluminum lapped and polished disk. These disks are subjected to 40khz ultrasonic cleaning in aqueous solutions with moderate temperature, often resulting in pitting caused by cavitation that removes the base material from the surface of the aluminum disk. As discussed above, one solution to this problem is to raise the temperature of the aqueous



1 solution to above 90°C. This causes the energy in each cavitation implosion to be less than  
2 the energy which typically removes base material from the aluminum disk. It is important,  
3 however, to keep the temperature below a value (typically 95°C) which provides a cavitation  
4 implosion that is strong enough to remove the contamination. Another solution to the  
5 problem is to use a higher frequency ultrasound. A 72khz ultrasonic system typically has the  
6 proper energy level in each cavitation implosion, with moderate temperature aqueous  
7 solutions, to remove contamination without removing base material from the lapped and  
8 polished aluminum disk.

9  
10 In the prior art, wet bench systems often consist of several low frequency ultrasonic  
11 and/or megasonic tanks with different chemistries disposed therein. For example, a cleaning  
12 tank followed by two rinsing tanks, usually in a reverse cascading configuration, is a common  
13 wet bench configuration. In wet bench systems, there is an optimum value for the energy in  
14 each cavitation implosion: the highest energy cavitation implosion that does not cause  
15 cavitation damage to the part being processed or cleaned. However, because different  
16 chemistries are used in different tanks in the wet bench system, the energy in each cavitation  
17 implosion, for a given frequency, will be different in each tank. Therefore, not all tanks will  
18 have the optimum value of energy in each cavitation implosion. This problem has been  
19 addressed in the prior art by using different frequency ultrasonics in the different tanks. For  
20 example, the cleaning tank can have a chemistry with low surface tension, where a low  
21 frequency such as 40khz gives the optimum energy in each cavitation implosion. The rinsing  
22 tanks, on the other hand, might use DI water, which has a high surface tension; and thus  
23 72khz ultrasonics may be needed to match the energy of the 40khz tank for each cavitation  
24 implosion.

25  
26 In single chamber process systems, different chemistries are pumped in and out of one  
27 tank. Because such process systems typically generate single or narrow band frequencies, or  
28 frequencies in a finite bandwidth, the energy in each cavitation implosion is optimum for one

1 chemistry and not generally optimum for the other chemistries. Such systems are therefore  
2 relatively inefficient for use with many different chemistries.

3  
4 Certain prior art ultrasonic systems generate ultrasonic frequencies in two or more  
5 unconnected frequencies, such as 40khz and 68khz. Although these systems had great  
6 commercial appeal, experimental results have showed little or no merit to these multi-  
7 frequency systems. Such systems tend to have all of the problems listed above, whereby the  
8 cleaning and damaging aspects of ultrasound are generally dependent upon a single  
9 frequency. That is, for example, if the higher frequency provides adequate cleaning, without  
10 damage, the lower frequency may cause cavitation damage to the part. By way of a further  
11 example, if the lower frequency provides cleaning without damage, then the higher frequency  
12 has little or no practical value.

13  
14 Cavitation damage can also occur when the delicate parts are removed from an  
15 operating ultrasonic bath. This damage occurs when the ultrasound reflects off of the liquid-  
16 air interface at the top of the tank to create non-uniform hot spots, i.e., zones of intense  
17 cavitation. The prior art has addressed this problem by turning the ultrasonics off before  
18 passing a delicate part through the liquid-air interface.

19  
20 Low frequency resonant damage is a relatively new phenomenon. The prior art has  
21 focused on solving the other, more significant problems - i.e., ultrasonic frequency resonance  
22 and cavitation damage - before addressing the low frequency resonant effects of an ultrasonic  
23 system. However, the prior art solutions to low frequency ultrasonic damage are, in part, due  
24 to a reaction to the problems associated with 25khz to 50khz ultrasound, described above.  
25 Specifically, the prior art has primarily focused on utilizing high frequency ultrasound in the  
26 processing and cleaning of semiconductor wafers and other delicate parts. These high  
27 frequency ultrasonic systems are single-frequency, continuous wave (CW) systems which  
28 operate from 600khz to about 2Mhz, a frequency range which is referred to as "megasonics"  
29 in the prior art.

1  
2 One such megasonic system is disclosed in U.S. Patent No. 3,893,869. The  
3 transducers of this system and other similar systems are typically 0.1 inch thick and are  
4 unclamped piezoelectric ceramics driven at their resonant frequency by a single frequency  
5 continuous-wave generator. All the techniques described above, e.g., material selections,  
6 tank configurations, and bonding techniques, and used with lower frequency ultrasonics were  
7 employed in the megasonic frequency systems of the prior art. For example, because of the  
8 aggressive chemistries used, quartz or Teflon tanks with a transducerized quartz window  
9 became a common configuration adapted from lower frequency ultrasonic systems.

10  
11 As described earlier and disclosed in U.S. Patent No. 4,118,649, the bonding of  
12 piezoelectric shapes to a tank, plate, window or immersible, by epoxy, were the common  
13 ways to integrate megasonic transducers within a treatment tank. One alternative is disclosed  
14 by Cook in U.S. Patent No. 4,527,901, where the ceramic is fired, and then polarized, as part  
15 of the tank assembly. Another prior art alternative to the bonding a piezoelectric shape by  
16 epoxy is to mold or cast the piezoelectric shape into the product. For example, one prior art  
17 system utilizes a piezoelectric circle that has been injection-molded into a tank assembly.  
18 The prior art also suggests that a piezoelectric rectangle could be cast into a quartz window;  
19 however, in this case, poling or repoling the ceramic after casting may be necessary if it  
20 exceeds its curie point.

21  
22 The megasonic systems of the prior art overcame many of the disadvantages and  
23 problems associated with 25khz to 50khz systems. First, because the energy in each  
24 cavitation implosion decreases with increasing frequency, damages due to cavitation  
25 implosion have been reduced or eliminated. Instead of cavitation implosion, megasonic  
26 systems depend on the microstreaming effect present in ultrasonic fields to give enhanced  
27 processing or cleaning. Resonant effects, although theoretically present, are minimal because  
28 the geometries of the delicate parts are typically not resonant at megasonic frequencies. As

1 geometries become smaller, however, such as in state-of-the-art equipment, certain prior art  
2 megasonic systems have had to increase their operating frequencies to 2Mhz or greater.

3  
4 An alternative to higher frequency megasonics is to optimize the ultrasonic energies  
5 with amplitude modulation (AM) of a frequency modulated (FM) wave. Such systems  
6 operate by adjusting one of seven ultrasonic generator parameters - center frequency,  
7 bandwidth, sweep time, train time, degas time, burst time, and quiet time - to adjust one or  
8 more of the following characteristics within the liquid: energy in each cavitation implosion,  
9 average cavitation density, cavitation density as a function of time, cavitation density as a  
10 function of position in the tank and average gaseous concentration.

11  
12 When megasonic systems became popular as a solution to cavitation and resonant  
13 damages caused by lower frequency ultrasonic systems, the prior art suggests that even  
14 higher frequencies be utilized in the removal of smaller, sub-micron particulate  
15 contamination. Recent data and physical understanding of the megasonic process, however,  
16 suggest that this is not the case. The microstreaming mechanism upon which megasonics  
17 depends penetrates the boundary layer next to a semiconductor wafer and relies on a pumping  
18 action to continuously deliver fresh solution to the wafer surface while simultaneously  
19 removing contamination and spent chemistry. Cleaning or processing with megasonics  
20 therefore depends upon (a) the chemical action of the particular cleaning, rinsing, or  
21 processing chemistry in the megasonics tank, and (b) the microstreaming which delivers the  
22 chemistry to the surface of the part being processed, rinsed, or cleaned.

23  
24 However, because microstreaming is produced in all high intensity ultrasonic fields in  
25 liquids, it can be expected that submicron size particle removal will occur in any high  
26 intensity ultrasonic field. When experiments were done where the problems of non-  
27 uniformity, high cavitation energy, and resonance were overcome by ultrasonic techniques  
28 such as those taught by U.S. Patent No. 4,736,130, the data showed effective submicron

1 particle removal at all ultrasonic frequencies used for semiconductor wafer cleaning and  
2 processing.

3  
4 One problem with prior art megasonic systems relates to the transducer design and  
5 operation frequency. In prior art megasonic systems, the commonly available 0.1 inch thick  
6 piezoelectric ceramic shapes are bonded to a typical tank or gasketed plate and have a  
7 fundamental resonant frequency in the 600khz to 900khz frequency range. The main  
8 difference between these megasonic transducers and the 25khz or 40khz transducers is that  
9 the lower frequency transducers are clamped systems, i.e., where the piezoelectric ceramic is  
10 always under compression, whereas the megasonic transducers are unclamped. Because the  
11 megasonic transducers are unclamped, the piezoelectric ceramics go into tension during its  
12 normal operation, reducing the transducer's reliability. This remains a significant problem  
13 with prior art megasonic systems.

14  
15 More particularly, ceramic is very strong under compression, but weak and prone to  
16 fracture when put into tension. When a clamped transducer is made, the front driver and the  
17 backplate compress the piezoelectric ceramic by means of a bolt or a number of bolts.  
18 However, the front driver and the backplate become part of the piezoelectric resonant  
19 structure, and operate to lower the resonant frequency of the combined part. The prior art  
20 clamped ultrasonic transducer structures resonate at fundamental frequencies well below the  
21 megasonic frequencies, and generally at 90khz and below.

22  
23 Therefore, one significant problem with megasonic systems and equipment is overall  
24 reliability. The megasonic piezoelectric ceramic is put into tension at 600,000 times per  
25 second (i.e., 600khz), at least, during operation. This tension causes the ceramics to crack  
26 because it weakens and fatigues the material with repeated cycles.

27  
28 Two other problems of prior art megasonic systems relate to the nature of high  
29 frequency sound waves in a liquid. Sound waves with frequencies above 500khz travel like a

1 beam within liquid, and further exhibit high attenuation. This beam effect is a problem  
2 because it is very difficult to uniformly fill the process or cleaning tank with the acoustic  
3 field. Therefore, the prior art has devised techniques to compensate for the beam effect, such  
4 as by (a) spreading the sound around the tank through use of acoustic lenses, or by (b)  
5 physically moving the parts through the acoustic beam. The beam and attenuation effects of  
6 megasonic systems result in non-uniform processing, and other undesirable artifacts.

7  
8 In the last ten years, several manufacturers of prior art ultrasonic systems have  
9 introduced frequency-sweeping ultrasonic generators with certain frequencies in the 25khz to  
10 72khz frequency range. Such systems overcome many of the problems associated in the prior  
11 art. By way of example, many or all of the damaging standing waves and resonances are  
12 eliminated by these frequency-sweeping ultrasonic systems. These systems reduce resonant  
13 damages by sweeping the frequencies fast enough, and over a large enough bandwidth, so  
14 that it greatly reduces the likelihood of having resonances within the tank. A rapid frequency  
15 sweeping system generates each cycle of sound (or in some cases, each half cycle of sound)  
16 at a significantly different frequency from the preceding cycle of sound (or half cycle of  
17 sound). Therefore, the build up of resonant energy required to impart a resonance amplitude  
18 within the part rarely or never occurs.

19  
20 Another advantage of frequency sweeping ultrasonic systems is that they increase the  
21 ultrasonic activity in the tank because there is less loss due to wave cancellation. One of the  
22 first frequency sweeping ultrasonic generators had a bandwidth of 2khz, a sweep rate of  
23 100hz, and a center frequency of 40khz. Accordingly, at a frequency change 400khz per  
24 second - i.e., two kilohertz sweeping up from 39khz to 41khz, plus two kilohertz sweeping  
25 down from 41khz to 39khz, times 100 times per second equals 400khz per second - the  
26 increased ultrasonic activity was able to cavitate semi-aqueous solvents which were  
27 previously impossible to continuously cavitate with commercially available conventional  
28 ultrasonic generators.

1           The frequency-sweeping activity in the prior art was so significant that by 1991 every  
2 major ultrasonic manufacture was shipping 40khz generators that changed frequency at  
3 frequency sweep rates of up to 4.8Mhz per second. This rapid sweeping of frequency  
4 provided good ultrasonic activity even at continuous wave (CW) operation. By way of  
5 example, one 10kilowatt, 40khz generator in the prior art operated directly from a rectified  
6 three-phase power signal which provided a 800khz per second CW frequency-sweeping  
7 system that had superior performance as compared to AM single frequency ultrasonic  
8 systems.

9  
10           Although the main problems with lower frequency ultrasonics were solved by  
11 frequency sweeping, cavitation damage could occur in any process where the energy in each  
12 cavitation implosion was strong enough to remove an atom or a molecule from the surface of  
13 the semiconductor wafer or the delicate part. As disclosed in U.S. Patent No. 4,736,130,  
14 system optimization at lower frequency ultrasonics permitted successful processing of many  
15 delicate parts because it was possible to maximize the microstreaming effects while  
16 minimizing adverse cavitation effects. However, the potential for cavitation damage remains  
17 a concern of the industry.

18  
19           One important limitation to further improvement of ultrasonic processes is the low  
20 frequency and the narrow bandwidth of clamped piezoelectric transducers. For example,  
21 typical clamped or unclamped prior art transducers provide about 4khz in overall bandwidth.  
22 One other important limitation of ultrasonic processes is that although amplitude control is  
23 known to be beneficial, inexpensive and uncomplicated ways of providing AM are generally  
24 not available.

25  
26           Other problems exist in the prior art in that certain systems are driven by more than  
27 one ultrasonic generator. Such generators typically operate to either (a) drive the same tank,  
28 or (b) drive multiple tanks in the same system. Although the generators are typically set to the  
29 same sweep rate, the independent generators will never have exactly the same sweep rate.

1 This causes another low frequency resonance problem within an ultrasonic tank or system. In  
2 addition, one problem with multiple tanks and multiple generators is that some of the  
3 ultrasound from one tank is coupled through connecting structure to the other tank(s). This  
4 creates unwanted cross-talk and negatively affects the desired cleaning or processing within  
5 the tank.

6  
7 In particular, prior art multi-generator systems sometimes create an undesirable beat  
8 frequency which causes low frequency resonance in susceptible parts. For example, consider  
9 two sweeping frequency generators, each with sweep rates of approximately 10hz sweeping  
10 over a bandwidth of 4khz with a center frequency of 40khz. Now consider a delicate part to  
11 be cleaned that has a low frequency resonance at one kilohertz. The following condition will  
12 occur periodically: one generator will be changing frequency from 38khz to 41khz, while the  
13 other generator is changing frequency from 39khz to 42khz. In this example, this will occur  
14 for about 37.5 milliseconds. Since the two frequencies in the tank or system are about one  
15 kilohertz apart, a beat frequency of about one kilohertz is produced. The period of one  
16 kilohertz is one millisecond, therefore a string of thirty-seven beats at about one kilohertz are  
17 produced. This is sufficient to setup a destructive resonance in a delicate part with a one  
18 kilohertz resonance

19  
20 It is, therefore, an object of the invention to provide ultrasonic systems which reduce  
21 or eliminate the problems in the prior art.

22  
23 Another object of the invention is to provide improvements to ultrasonic generators,  
24 to transducers applying ultrasound energy to liquids, and to methods for reducing the  
25 damage to delicate parts.

26  
27 It is still another object of the invention to provide methodology for applying  
28 ultrasound to liquid in a manner which is compatible with both the tank chemistry and the  
29 part under process.



1  
2 Still another object of the invention to provide a method of supplying suitable  
3 energies in each cavitation implosion, in a single chamber process system, where different  
4 chemistries are used in different parts of the process.

5  
6 Another object of the invention is to provide an ultrasonic generator that reduces the  
7 repetition of low frequency components from an ultrasonic bath to reduce or eliminate low  
8 frequency resonances within the bath.

9  
10 One objective of this invention is to overcome certain disadvantages of prior art  
11 megasonic systems while retaining certain advantages of megasonic cleaning and/or  
12 processing.

13  
14 It is a further objective of this invention to provide ultrasonic transducer arrays which  
15 supply ultrasonic energy with microstreaming and without significant cavitation implosion.

16  
17 Still another object of this invention is to provide methodology of improved  
18 amplitude control in ultrasonic systems.

19  
20 Another object of the invention is to provide systems which reduce or eliminate  
21 beating and/or cross-talk within a liquid caused by simultaneous operation of a plurality of  
22 generators.

23  
24 These and other objects of the invention will be apparent from the description which  
25 follows.

26  
27 Summary of the Invention

1           As used herein, "ultrasound" and "ultrasonic" generally refer to acoustic disturbances  
2 in a frequency range above about eighteen kilohertz and which extend upwards to over two  
3 megahertz. "Lower frequency" ultrasound, or "low frequency" ultrasound mean ultrasound  
4 between about 18khz and 90khz. "Megasonics" or "megasonic" refer to acoustic disturbances  
5 between 600khz and 2Mhz. As discussed above, the prior art has manufactured "low  
6 frequency" and "megasonic" ultrasound systems. Typical prior art low frequency systems, for  
7 example, operate at 25khz, 40khz, and as high as 90khz. Typical prior art megasonic systems  
8 operate between 600khz and 1Mhz. Certain aspects of the invention apply to low frequency  
9 ultrasound and to megasonics. However, certain aspects of the invention apply to ultrasound  
10 in the 100khz to 350khz region, a frequency range which is sometimes denoted herein as  
11 "microsonics."

12  
13           As used herein, "resonant transducer" means a transducer operated at a frequency or  
14 in a range of frequencies that correspond to a one-half wavelength ( $\lambda$ ) of sound in the  
15 transducer stack. "Harmonic transducer" means a transducer operated at a frequency or in a  
16 range of frequencies that correspond to  $1\lambda$ ,  $1.5\lambda$ ,  $2\lambda$  or  $2.5\lambda$  of sound, and so on, in the  
17 transducer stack. "Bandwidth" means the range of frequencies in a resonant or harmonic  
18 region of a transducer over which the acoustic power output of a transducer remains between  
19 50% and 100% of the maximum value.

20  
21           As used herein, a "delicate part" refers to those parts which are undergoing a  
22 manufacture, process, or cleaning operation within liquid subjected to ultrasonic energy. By  
23 way of example, one delicate part is a semiconductor wafer which has extremely small  
24 features and which is easily damaged by cavitation implosion. A delicate part often defines  
25 components in the computer industry, including disk drives, semiconductor components, and  
26 the like.

27  
28           As used herein, "khz" refers to kilohertz and a frequency magnitude of one thousand  
29 hertz. "Mhz" refers to megahertz and a frequency magnitude of one million hertz.

1  
2 As used herein, "sweep rate" or "sweep frequency" refer to the rate or frequency at  
3 which a generator and transducer's frequency is varied. That is, it is generally undesirable to  
4 operate an ultrasonic transducer at a fixed, single frequency because of the resonances created  
5 at that frequency. Therefore, an ultrasonic generator can sweep (i.e., linearly change) the  
6 operational frequency through some or all of the available frequencies within the transducer's  
7 bandwidth at a "sweep rate." Accordingly, particular frequencies have only short duration  
8 during the sweep cycle (i.e., the time period for sweeping the ultrasound frequency through a  
9 range of frequencies within the bandwidth). "Sweep the sweep rate" or "double sweeping" or  
10 "dual sweep" refer to an operation of changing the sweep rate as a function of time. In accord  
11 with the invention, "sweeping the sweep rate" generally refers to the operation of sweeping  
12 (i.e., linearly changing) the sweep rate so as to reduce or eliminate resonances generated at  
13 the sweep frequency.

14  
15 The present invention concerns the applied uses of ultrasound energy, and in  
16 particular the application and control of ultrasonics to clean and process delicate parts, e.g.,  
17 semiconductor wafers, within a liquid. Generally, in accord with the invention, one or more  
18 ultrasonic generators drive one or more ultrasonic transducers, or arrays of transducers,  
19 coupled to a liquid to clean and/or process the delicate part. The liquid is preferably held  
20 within a tank; and the transducers mount on or within the tank to impart ultrasound into the  
21 liquid. In this context, the invention is particularly directed to one or more of the following  
22 aspects and advantages:

23  
24 (1) By utilizing harmonics of certain clamped ultrasound transducers, the invention  
25 generates, in one aspect, ultrasound within the liquid in a frequency range of between about  
26 100khz to 350khz (i.e., "microsonic" frequencies). This has certain advantages over the prior  
27 art. In particular, unlike prior art low frequency ultrasound systems which operate at less  
28 than 100khz, the invention eliminates or greatly reduces damaging cavitation implosions  
29 within the liquid. Further, the transducers operating in this frequency range provide

relatively uniform microstreaming, such as provided by megasonics; but they are also relatively rugged and reliable, unlike megasonic transducer elements. In addition, and unlike megasonics, microsonic waves are not highly collimated, or "beam-like," within liquid; and therefore efficiently couple into the geometry of the ultrasonic tank. Preferably, the application of microsonic frequencies to liquid occurs simultaneously with a sweeping of the microsonic frequency within the transducer's harmonic bandwidth. That is, microsonic transducers (clamped harmonic transducers) are most practical when there is a sweep rate of the applied microsonic frequency. This combination reduces or eliminates (a) standing waves within the liquid, (b) other resonances, (c) high energy cavitation implosions; and (d) non-uniform sound fields, each of which is undesirable for cleaning or processing semiconductor wafers and delicate parts.

(2) The ultrasound transducers or arrays of the invention typically have a finite bandwidth associated with the range of frequencies about a resonant or harmonic frequency. When driven at frequencies within the bandwidth, the transducers generate acoustic energy that is coupled into the liquid. In one aspect, the invention drives the transducers such that the frequency of applied energy has a sweep rate within the bandwidth; and that sweep rate is also varied so that the sweep rate is substantially non-constant during operation. For example, the sweep rate can change linearly, randomly, or as some other function of time. In this manner, the invention reduces or eliminates resonances which are created by transducers operating with a single sweep rate, such as provided in the prior art.

(3) At least one ultrasound generator of the invention utilizes amplitude modulation (AM). However, unlike the prior art, this AM generator operates by selectively changing the AM frequency over time. In a preferred aspect of the invention, the AM frequency is swept through a range of frequencies which reduce or eliminate low frequency resonances within the liquid and the part being processed. Accordingly, the AM frequency is swept through a range of frequencies; and this range is typically defined as about 10-40% of the optimum AM frequency. The optimum AM frequency is usually between about 1hz and 10khz. Therefore,

1 for example, if the optimum AM frequency is 1khz, then the AM frequency is swept through  
2 a frequency range of between about 850hz and 1150hz. In addition, the rate at which these  
3 frequencies are varied is usually less than about 1/10th of the optimum AM frequency. In this  
4 example, therefore, the AM sweep rate is about 100hz. These operations of sweeping the  
5 AM frequency through a range of frequencies and at a defined AM sweep rate reduce or  
6 eliminate unwanted resonances which might otherwise occur at the optimum AM frequency.  
7 In another aspect of the invention, for delicate parts with very low frequency resonances, the  
8 AM frequency is changed randomly or the AM sweep rate is swept at a function of time with  
9 a frequency about 1/10th of the AM sweep rate.

10  
11 (4) The invention provides AM control by selecting a portion of the rectified power line  
12 frequency (e.g., 60hz in the United States and 50hz in Europe). In one aspect, this AM  
13 control is implemented by selecting a portion of the leading quarter sinusoid in a full wave  
14 amplitude modulation pattern that ends at the required amplitude in the zero to 90° and the  
15 180° to 270° regions. Another AM control is implemented by selecting a portion of the  
16 leading quarter sinusoid in a half wave amplitude modulation pattern that ends at the required  
17 amplitude in the zero to 90° region.

18  
19 (5) The invention can utilize several tanks, transducers and generators simultaneously to  
20 provide a wet bath of different chemistries for the delicate part. In one aspect, when two or  
21 more generators are operating at the same time, the invention synchronizes their operation to  
22 a common FM signal so that each generator can be adjusted, through AM, to control the  
23 process characteristics within the associated tank. In this manner, undesirable beating effects  
24 or cross-coupling between multiple tanks are reduced or eliminated. In a preferred aspect, a  
25 master generator provides a common FM signal to the other generators, each operating as a  
26 slave generator coupled to the master generator, and each slave generator provides AM  
27 selectively. In addition, because the transducers in the several tanks are sometimes swept  
28 through the frequencies of the transducer's bandwidth, the FM control maintains overall  
29 synchronization even though varying AM is applied to the several transducers. The multi-

generator FM synchronization also applies to single tank ultrasonic systems. That is, the invention supports the synchronized operation of a plurality of generators that are connected to a single tank. In this case, each generator has an associated harmonic transducer array and is driven with a common FM signal and AM signal so that the frequencies within the tank are synchronized, in magnitude and phase, to reduce or eliminate unwanted resonances which might otherwise occur through beating effects between the multiple generators and transducers.

(6) In another aspect, the invention utilizes two or more transducers, in combination, to broaden the overall bandwidth of acoustical energy applied to the liquid around the primary frequency or one of the harmonics. For example, the invention of one aspect has two clamped transducers operating at their first, second third, or fourth harmonic frequency between about 100khz and 350khz. The center harmonic frequency of each is adjusted so as to be different from each other. However, their bandwidths are made to overlap such that an attached generator can drive the transducers, in combination, to deliver ultrasound to the liquid in a broader bandwidth. In a preferred aspect, two or more transducers, or transducer arrays, operate at unique harmonic frequencies and have finite bandwidths that overlap with each of the other transducers. If, for example, each transducer has a bandwidth of 4khz, then two such transducers can approximately provide a 8khz bandwidth, and three such transducers can approximately provide a 12khz bandwidth, and so on.

(7) In one aspect, the invention provides a single tank system which selects a desired frequency, or range of frequencies, from a plurality of connected ultrasonic generators. Specifically, two or more generators, each operating or optimized to generate a range of frequencies, are connected to a mux; and the system selects the desired frequency range, and hence the right generator, according to the cavitation implosion energy that is desired within the tank chemistry.

(8) The invention has additional and sometimes greater advantages in systems and methods which combine one or more of the features in the above paragraphs (1) through (7). By way of example, one particularly useful system combines two or more microsonic transducers (i.e., paragraph 1) to create broadband microsonics (i.e., paragraph 6) within liquid. Such a system can further be controlled to provide a specific amplitude modulation (i.e., paragraph 4). Other particularly advantageous systems and methods of the invention are realized with the following combinations: (2) and (4); (1), (2) and (4); and (1) and (2) with frequency sweeping of the microsonic frequency.

The following patents, each incorporated herein by reference, provide useful background to the invention in the area of ultrasonic generators: 3,152,295; 3,293,456; 3,629,726; 3,638,087; 3, 648,188; 3,651,352; 3,727,112; 3,842,340; 4,044,297; 4,054,848; 4,069,444; 4,081,706; 4,109,174; 4,141,608; 4,156,157; 4,175,242; 4,275,363; and 4,418,297. Further, U.S. Patent Nos. 4,743,789 and 4,736,130 provide particularly useful background in connection with ultrasonic generators that are suitable for use with certain aspects of the invention, and are, accordingly incorporated herein by reference.

Clamped ultrasonic transducers suitable for use with the invention are known in the art. For example, the following patents, each incorporated herein by reference, provide useful background to the invention: 3,066,232; 3,094,314; 3,113,761; 3,187,207; 3,230,403; 3,778,758; 3,804,329 and RE 25,433.

Techniques for mounting or affixing transducers within the tank, and of arranging the transducer and/or tank geometry are, for example, described in U.S. Patent Nos. 4,118,649; 4,527,901; 4,543,130; and 4,836,684. Each of these patents is also incorporated by reference.

Single chamber ultrasonic processing systems are described, for example, in U.S. Patent Nos. 3,690,333; 4,409,999; 5,143,103; and 5,201,958. Such systems provide

1 additional background to the invention and are, accordingly, incorporated herein by  
2 reference.

3  
4 In one aspect, the invention provides a system for delivering broadband ultrasound to  
5 liquid. The system includes first and second ultrasonic transducers. The first transducer has a  
6 first frequency and a first ultrasound bandwidth, and the second transducer has a second  
7 frequency and a second ultrasound bandwidth. The first and second bandwidths are  
8 overlapping with each other and the first frequency is different from the second frequency.  
9 An ultrasound generator drives the transducers at frequencies within the bandwidths.  
10 Together, the first and second transducers and the generator produce ultrasound within the  
11 liquid and with a combined bandwidth that is greater than either of the first and second  
12 bandwidths.

13  
14 In another aspect, the system of the invention includes a third ultrasonic transducer  
15 that has a third frequency and a third ultrasound bandwidth. The third bandwidth is  
16 overlapping with at least one of the other bandwidths, and the third frequency is different  
17 from the first and second frequencies. The generator in this aspect drives the third transducer  
18 within the third bandwidth so as to produce ultrasound within the liquid and with a combined  
19 bandwidth that is greater than any of the first, second and third bandwidths.

20  
21 Preferably, each of the transducers are clamped so as to resist material strain and  
22 fatigue. In another aspect, each of the first and second frequencies are harmonic frequencies  
23 of the transducer's base resonant frequency. In one aspect, these harmonic frequencies are  
24 between about 100khz and 350khz.

25  
26 In another aspect, the system includes at least one other synergistic ultrasonic  
27 transducer that has a synergistic frequency and a synergistic ultrasound bandwidth. As above,  
28 the synergistic bandwidth is overlapping with at least one of the other bandwidths, and the  
29 synergistic frequency is different from the first and second frequencies. The generator drives



1 the synergistic transducer within the synergistic bandwidth so as to produce ultrasound within  
2 the liquid and with a combined bandwidth that is greater than any of the other bandwidths. In  
3 one aspect, this synergistic frequency is a harmonic frequency between about 100khz and  
4 350khz.

5  
6 In other aspects, the bandwidths of combined transducers overlap so that, in  
7 combination, the transducers produce ultrasonic energy at substantially all frequencies within  
8 the combined bandwidth. Preferably, the combined operation provides ultrasound with  
9 relatively equal power for any frequency in the combined bandwidth. Using the full width  
10 half maximum (FWHM) to define each bandwidth, the bandwidths preferably overlap such  
11 that the power at each frequency within the combined bandwidth is within a factor of two of  
12 ultrasonic energy produced at any other frequency within the combined bandwidth.

13  
14 In another aspect, a system is provided for delivering ultrasound to liquid. The  
15 system has an ultrasonic transducer with a harmonic frequency between about 100khz and  
16 350khz and within an ultrasound bandwidth. A clamp applies compression to the transducer.  
17 An ultrasound generator drives the transducer at a range of frequencies within the bandwidth  
18 so as to produce ultrasound within the liquid.

19  
20 In still another aspect, the system can include at least one other ultrasonic transducer  
21 that has a second harmonic frequency within a second bandwidth. As above, the second  
22 frequency is between about 100khz and 350khz, and the second bandwidth is overlapping, in  
23 frequency, with the ultrasound bandwidth. The generator drives the transducers at frequencies  
24 within the bandwidths so as to produce ultrasound within the liquid and with a combined  
25 bandwidth that is greater than the bandwidth of a single transducer.

26  
27 Another aspect of the invention provides a system for delivering ultrasound to liquid.  
28 In such a system, one or more ultrasonic transducers have an operating frequency within an  
29 ultrasound bandwidth. An ultrasound generator drives the transducers at frequencies within

1 the bandwidth, and also changes the sweep rate of the frequency continuously so as to  
2 produce non-resonating ultrasound within the liquid.

3  
4 Preferably, the generator of the invention changes the sweep rate frequency in one of  
5 several ways. In one aspect, for example, the sweep rate is varied as a function of time. In  
6 another aspect, the sweep rate is changed randomly. Typically, the sweep rate frequency is  
7 changed through a range of frequencies that are between about 10-50% of the optimum  
8 sweep rate frequency. The optimum sweep rate frequency is usually between about 1hz and  
9 1.2khz; and, therefore, the range of frequencies through which the sweep rate is varied can  
10 change dramatically. By way of example, if the optimum sweep rate is 500hz, then the range  
11 of sweep rate frequencies is between about 400hz and 600hz; and the invention operates by  
12 varying the sweep rate within this range linearly, randomly, or as a function of time, so as to  
13 optimize processing characteristics within the liquid.

14  
15 The invention further provides a system for delivering ultrasound to liquid. This  
16 system includes one or more ultrasonic transducers, each having an operating frequency  
17 within an ultrasound bandwidth. An amplitude modulated ultrasound generator drives the  
18 transducers at frequencies within the bandwidth. A generator subsystem also changes the  
19 modulation frequency of the AM, continually, so as to produce ultrasound within the liquid to  
20 prevent low frequency resonances at the AM frequency.

21  
22 Preferably, the subsystem sweeps the AM frequency at a sweep rate between about  
23 1hz and 100hz. For extremely sensitive parts and/or tank chemistries, the invention can  
24 further sweep the AM sweep rate as a function of time so as to eliminate possible resonances  
25 which might be generated by the AM sweep rate frequency. This sweeping of the AM  
26 sweep rate occurs for a range of AM sweep frequencies generally defined by 10-40% of the  
27 optimum AM sweep rate. For example, if the optimum AM sweep rate is 150hz, then one  
28 aspect of the invention changes the AM sweep rate through a range of about 130hz to 170hz.

1 In one aspect, the invention also provides amplitude control through the power lines.  
2 Specifically, amplitude modulation is achieved by selecting a portion of a leading quarter  
3 sinusoid, in a full wave amplitude modulation pattern, that ends at a selected amplitude in a  
4 region between zero and 90° and between 180° and 270° of the sinusoid. Alternatively,  
5 amplitude control is achieved by selecting a portion of a leading quarter sinusoid, in a half  
6 wave amplitude modulation pattern, that ends at a selected amplitude between zero and 90°  
7 of the sinusoid.

8  
9 In still another aspect, a system of the invention can include two or more ultrasound  
10 generators that are synchronized in magnitude and phase so that there is substantially zero  
11 frequency difference between signals generated by the generators. Preferably, a timing  
12 signal is generated between the generators to synchronize the signals. In one aspect, a FM  
13 generator provides a master frequency modulated signal to each generator to synchronize the  
14 signals from the generators.

15  
16 A generator of the invention can also be frequency modulated over a range of  
17 frequencies within the bandwidth of each transducer. In another aspect, the frequency  
18 modulation occurs over a range of frequencies within the bandwidth of each transducer, and  
19 the generator is amplitude modulated over a range of frequencies within the bandwidth of  
20 each transducer.

21  
22 The systems of the invention generally include a chamber for holding the solution or  
23 liquid which is used to clean or process objects therein. The chamber can include, for  
24 example, material such as 316L stainless steel, 304 stainless steel, polytetrafluoroethylene,  
25 fluorinated ethylene propylene, polyvinylidene fluoride, perfluoroalkoxy, polypropylene,  
26 polyetheretherketone, tantalum, teflon coated stainless steel, titanium, hastalloy, and mixtures  
27 thereof.

1           It is preferable that the transducers of the system include an array of ultrasound  
2 transducer elements.

3  
4           The invention also provides a method of delivering broadband ultrasound to liquid,  
5 including the steps of: driving a first ultrasound transducer with a generator at a first  
6 frequency and within a first ultrasound bandwidth, and driving a second ultrasound  
7 transducer with the generator at a second frequency within a second ultrasound bandwidth  
8 that overlaps at least part of the first bandwidth, such that the first and second transducers, in  
9 combination with the generator, produce ultrasound within the liquid and with a combined  
10 bandwidth that is greater than either of the first and second bandwidths.

11  
12           In other aspects, the method includes the step of compressing at least one of the  
13 transducers, and/or the step of driving the first and second transducers at harmonic  
14 frequencies between about 100khz and 350khz.

15  
16           Preferably, the method includes the step of arranging the bandwidths to overlap so  
17 that the transducers and generator produce ultrasonic energy, at each frequency, that is  
18 within a factor of two of ultrasonic energy produced by the transducers and generator at any  
19 other frequency within the combined bandwidth.

20  
21           The application of broadband ultrasound has certain advantages. First, it increases the  
22 useful bandwidth of multiple transducer assemblies so that the advantages to sweeping  
23 ultrasound are enhanced. The broadband ultrasound also gives more ultrasonic intensity for a  
24 given power level because there are additional and different frequencies spaced further apart  
25 in the ultrasonic bath at any one time. Therefore, there is less sound energy cancellation  
26 because only frequencies of the same wavelength, the same amplitude and opposite phase  
27 cancel effectively.

1 In one aspect, the method of the invention includes the step of driving an ultrasonic  
2 transducer in a first bandwidth of harmonic frequencies centered about a microsonic  
3 frequency in the range of 100khz and 350khz. For protection, the transducer is preferably  
4 compressed to protect its integrity.

5  
6 Another method of the invention provides the following steps: coupling one or more  
7 ultrasonic transducers to the liquid, driving, with a generator, the transducers to an operating  
8 frequency within an ultrasound bandwidth, the transducers and generator generating  
9 ultrasound within the liquid, changing the frequency within the bandwidth at a sweep rate,  
10 and continuously varying the sweep rate as a function of time so as to reduce low frequency  
11 resonances.

12  
13 In other aspects, the sweep rate is varied according to one of the following steps:  
14 sweeping the sweep rate as a function of time; linearly sweeping the sweep rate as a function  
15 of time; and randomly sweeping the sweep rate. Usually, the optimum sweep frequency is  
16 between about 1hz and 1.2khz, and therefore, in other aspects, the methods of the invention  
17 change the sweep rate within a range of sweep frequencies centered about an optimum sweep  
18 frequency. Typically, this range is defined by about 10-50% of the optimum sweep  
19 frequency. For example, if the optimum sweep frequency is 800hz, then the range of sweep  
20 frequencies is between about 720hz and 880hz. Further, and in another aspect, the rate at  
21 which the invention sweeps the sweep rate within this range is varied at less than about  
22 1/10th of the optimum frequency. Therefore, in this example, the invention changes the  
23 sweep rate at a rate that is less than about 80hz.

24  
25 Another method of the invention provides for the steps of (a) generating a drive signal  
26 for one or more ultrasonic transducers, each having an operating frequency within an  
27 ultrasound bandwidth, (b) amplitude modulating the drive signal at a modulation frequency,  
28 and (c) sweeping the modulation frequency, selectively, as to produce ultrasound within the  
29 liquid.

1  
2       The invention is particularly useful as an ultrasonic system which couples acoustic  
3 energy into a liquid for purposes of cleaning parts, developing photosensitive polymers, and  
4 stripping material from surfaces. The invention can provide many sound frequencies to the  
5 liquid by sweeping the sound through the bandwidth of the transducers. This provides at least  
6 three advantages: the standing waves causing cavitation hot spots in the liquid are reduced or  
7 eliminated; part resonances within the liquid at ultrasonic frequencies are reduced or  
8 eliminated; and the ultrasonic activity in the liquid builds up to a higher intensity because  
9 there is less cancellation of sound waves.

10  
11       In one aspect, the invention provides an ultrasonic bath with transducers having at  
12 least two different resonant frequencies. In one configuration, the resonant frequencies are  
13 made so that the bandwidths of the transducers overlap and so that the impedance versus  
14 frequency curve for the paralleled transducers exhibit maximum flatness in the resonant  
15 region. For example, when a 40khz transducer with a 4.1khz bandwidth is put in parallel -  
16 i.e., with overlapping bandwidths - with a 44khz transducer with a 4.2khz bandwidth, the  
17 resultant bandwidth of the multiple transducer assembly is about 8 khz. If transducers with  
18 three different frequencies are used, the bandwidth is approximately three times the  
19 bandwidth of a single transducer.

20  
21       In another aspect, a clamped transducer array is provided with a resonant frequency of  
22 40khz and a bandwidth of 4 khz. The array has a second harmonic resonant frequency at  
23 104khz with a 4khz harmonic bandwidth. Preferably, the bandwidth of this second harmonic  
24 frequency resonance is increased by the methods described above for the fundamental  
25 frequency of a clamped transducer array.

26  
27       In one aspect, the invention provides a method and associated circuitry which  
28 constantly changes the sweep rate of an ultrasonic transducer within a range of values that is  
29 in an optimum process range. For example, one exemplary process can have an optimum

1 sweep rate in the range 380hz to 530hz. In accord with one aspect of the invention, this  
2 sweep rate constantly changes within the 380hz to 530hz range so that the sweep rate does  
3 not set up resonances within the tank and set up a resonance at that rate.

4  
5 The invention provides for several methods to change the sweep rate. One of the  
6 most effective methods is to generate a random change in sweep rate within the specified  
7 range. A simpler method is to sweep the sweep rate at some given function of time, e.g.,  
8 linearly. One problem with sweeping the sweep rate is that the sweeping function of time has  
9 a specific frequency which may itself cause a resonance. Accordingly, one aspect of the  
10 invention is to sweep this time function; however, in practice, the time function has a specific  
11 frequency lower than the lowest resonant frequency of the semiconductor wafer or delicate  
12 part, so there is little need to eliminate that specific frequency.

13  
14 Most prior art ultrasonic systems are amplitude modulated at a low frequency,  
15 typically 50hz, 60hz, 100hz, or 120hz. One ultrasonic generator, the proSONIK™ sold by  
16 Ney Ultrasonics Inc., and produced according to U. S. Patent No. 4,736,130, permits the  
17 generation of a specific amplitude modulation pattern that is typically between 50hz to 5khz.  
18 However, the specific amplitude modulation frequency can itself be a cause of low frequency  
19 resonance in an ultrasonic bath if the selected amplitude modulation frequency is a resonant  
20 frequency of the delicate part.

21  
22 Accordingly, one aspect of the invention solves the problem of delicate part resonance  
23 at the amplitude modulation frequency by randomly changing or sweeping the frequency of  
24 the amplitude modulation within a bandwidth of amplitude modulation frequencies that  
25 satisfy the process specifications. For cases where substantially all of the low frequencies  
26 must be eliminated, random changes of the modulation frequency are preferred. For cases  
27 where there are no resonances in a part below a specified frequency, the amplitude  
28 modulation frequency can be swept at a frequency below the specified frequency.

1 Random changing or sweeping of the amplitude modulation frequency inhibits low  
2 frequency resonances because there is little repetitive energy at a frequency within the  
3 resonant range of the delicate part or semiconductor wafer. Accordingly, a resonant condition  
4 does not build up, in accord with the invention, providing obvious advantages.

5  
6 The invention also provides relatively inexpensive amplitude control as compared to  
7 the prior art. One aspect of the invention provides amplitude control with a full wave or half  
8 wave amplitude modulated ultrasonic signal. For full wave, a section of the  $0^{\circ}$  to  $90^{\circ}$  and the  
9  $180^{\circ}$  to  $270^{\circ}$  quarter sinusoid is chosen which ends at the required (desired) amplitude. For  
10 example, at the zero crossover of the half sinusoid ( $0^{\circ}$  and  $180^{\circ}$ ), a monostable multivibrator  
11 is triggered. It is set to time out before  $90^{\circ}$  duration, and specifically at the required  
12 amplitude value. This timed monostable multivibrator pulse is used to select that section of  
13 the quarter sinusoid that never exceeds the required amplitude.

14  
15 In one aspect, the invention also provides an adjustable ultrasonic generator. One  
16 aspect of this generator is that the sweep rate frequency and the amplitude modulation pattern  
17 frequency are randomly changed or swept within the optimum range for a selected process.  
18 Another aspect is that the generator drives an expanded bandwidth clamped piezoelectric  
19 transducer array at a harmonic frequency from 100khz to 350khz.

20  
21 Such a generator provides several improvements in the problematic areas affecting  
22 lower frequency ultrasonics and megasonics: uncontrolled cavitation implosion, unwanted  
23 resonances, unreliable transducers, and standing waves. Instead, the system of the invention  
24 provides uniform microstreaming that is critical to semiconductor wafer and other delicate  
25 part processing and cleaning.

26  
27 In another aspect of the invention, an array of transducers is used to transmit sound  
28 into a liquid at its fundamental frequency, e.g., 40khz, and at each harmonic frequency, e.g.,  
29 72khz or 104khz. The outputs of generators which have the transducer resonant frequencies



1 and harmonic frequencies are connected through relays to the transducer array. One  
2 generator with the output frequency that most closely produces the optimum energy in each  
3 cavitation implosion for the current process chemistry is switched to the transducer array.

4  
5 In yet another aspect, the invention reduces or eliminates low frequency beat  
6 resonances created by multiple generators by synchronizing the sweep rates (both in  
7 magnitude and in phase) so that there is zero frequency difference between the signals  
8 coming out of multiple generators. In one aspect, the synchronization of sweep rate  
9 magnitude and phase is accomplished by sending a timing signal from one generator to each  
10 of the other generators. In another aspect, a master FM signal is generated that is sent to each  
11 "slave" power module, which amplifies the master FM signal for delivery to the transducers.  
12 At times, the master and slave aspect of the invention also provides advantages in eliminating  
13 or reducing the beat frequency created by multiple generators driving a single tank.

14  
15 However, when multiple generators are driving different tanks in the same system,  
16 this master and slave aspect may not be acceptable because the AM of the FM signal is  
17 usually different for different processes in the different tanks. Accordingly, and in another  
18 aspect, a master control is provided which solves this problem. The master control of the  
19 invention has a single FM function generator (sweeping frequency signal) and multiple AM  
20 function generators, one for each tank. Thus, every tank in the system receives the same  
21 magnitude and phase of sweep rate, but a different AM as set on the control for each  
22 generator.

23  
24 The invention also provides other advantages as compared to the prior art's methods  
25 for frequency sweeping ultrasound within the transducer's bandwidth. Specifically, the  
26 invention provides a sweeping of the sweep rate, within the transducer's bandwidth, such that  
27 low frequency resonances are reduced or eliminated. Prior art frequency sweep systems had a  
28 fixed sweep frequency that is selectable, once, for a given application. One problem with

1 such prior art systems is that the single low frequency can set up a resonance in a delicate  
2 part, for example, a read-write head for a hard disk drive.

3  
4 The invention also provides advantages in that the sweep frequency of the sweep rate  
5 can be adjusted to conditions within the tank, or to the configuration of the tank or transducer,  
6 or even to a process chemistry.

7  
8 The invention also has certain advantages over prior art single chamber ultrasound  
9 systems. Specifically, the methods of the invention, in certain aspects, use different frequency  
10 ultrasonics for each different chemistry so that the same optimum energy in each cavitation  
11 implosion is maintained in each process or cleaning chemistry. According to other aspects of  
12 the invention, this process is enhanced by selecting the proper ultrasonic generator frequency  
13 that is supplied at the fundamental or harmonic frequency of the transducers bonded to the  
14 single ultrasonic chamber.

15  
16 These and other aspects and advantages of the invention are evident in the description  
17 which follows and in the accompanying drawings.

18  
19 Brief Description of the Drawings

20  
21 A more complete understanding of the invention may be obtained by reference to the  
22 drawings, in which:

23  
24 Figure 1 shows a cut-away side view schematic of an ultrasound processing system  
25 constructed according to the invention;

26  
27 Figure 1A shows a top view schematic of the system of Figure 1;  
28

1        Figure 2 shows a schematic illustration of a multi-transducer system constructed  
2 according to the invention and used to generate broadband ultrasound in a combined  
3 bandwidth; Figure 2A graphically illustrates the acoustic disturbances produced by the two  
4 transducers of Figure 2; Figure 2B graphically illustrates the broadband acoustic  
5 disturbances produced by harmonics of a multi-transducer system constructed according to  
6 the invention;

7  
8        Figure 3 shows a block diagram illustrating one embodiment of a system constructed  
9 according to the invention;

10  
11        Figure 4 shows a schematic embodiment of the signal section of the system of Figure  
12 3;

13  
14        Figure 5A and 5B show a schematic embodiment of the power module section of the  
15 system of Figure 3;

16  
17        Figure 6 is a cross-sectional side view of a harmonic transducer constructed according  
18 to the invention and driven by the power module of Figures 5A and 5B; Figure 6A is a top  
19 view of the harmonic transducer of Figure 6;

20  
21        Figure 7 is a schematic illustration of an amplitude control subsystem constructed  
22 according to the invention; Figure 7A shows illustrative amplitude control signals generated  
23 by an amplitude control subsystem such as in Figure 7;

24  
25        Figure 8 shows a schematic illustration of an AM sweep subsystem constructed  
26 according to the invention; Figure 8A shows a typical AM frequency generated by an AM

1 generator; Figure 8B graphically shows AM sweep frequency as a function of time for a  
2 representative sweep rate, in accord with the invention;

3  
4 Figure 9 illustrates a multi-generator, multi-frequency, single tank ultrasound system  
5 constructed according to the invention; Figure 9A illustrates another multi-generator, single  
6 tank system constructed according to the invention;

7  
8 Figure 10 illustrates a multi-generator, common-frequency, single tank ultrasound  
9 system constructed according to the invention;

10  
11 Figure 11 illustrates a multi-tank ultrasound system constructed according to the  
12 invention; Figure 11A shows representative AM waveform patterns as controlled through the  
13 system of Figure 11; and

14  
15 Figures 12A, 12B and 12C graphically illustrate methods of sweeping the sweep rate  
16 in accord with the invention.

17  
18 Detailed Description of Illustrated Embodiments

19  
20 Figures 1 and 1A show schematic side and top views, respectively, of an ultrasound  
21 processing system 10 constructed according to the invention. An ultrasonic generator 12  
22 electrically connects, via electrical paths 14a, 14b, to an ultrasound transducer 16 to drive the  
23 transducer 16 at ultrasound frequencies above about 18khz, and usually between 40khz and  
24 350khz. Though not required, the transducer 16 is shown in Figure 1 as an array of  
25 transducer elements 18. Typically, such elements 18 are made from ceramic, piezoelectric,  
26 or magnetostrictive materials which expand and contract with applied voltages or current to  
27 create ultrasound. The transducer 16 is mounted to the bottom, to the sides, or within the

1 ultrasound treatment tank 20 through conventional methods, such as known to those skilled  
2 in the art and as described above. A liquid 22 fills the tank to a level sufficient to cover the  
3 delicate part 24 to be processed and/or cleaned. In operation, the generator 12 drives the  
4 transducer 16 to create acoustic energy 26 that couples into the liquid 22.

5  
6 Although the transducer 16 is shown mounted to the bottom of the tank 20, those  
7 skilled in the art will appreciate that other mounting configurations are possible and  
8 envisioned. The transducer elements 18 are of conventional design, and are preferably  
9 "clamped" so as to compress the piezoelectric transducer material.

10  
11 Figure 2 illustrates a two transducer system 30. Transducer 32a, 32b are similar to one  
12 of the elements 18, Figure 1. Transducer 32a includes two ceramic sandwiched elements 34,  
13 a steel back plate 38a, and a front drive plate 36a that is mounted to the tank 20'. Transducer  
14 32b includes two ceramic sandwiched elements 34, a steel back plate 38b, and a front drive  
15 plate 36b that is mounted to the tank 20'. Bolts 39a, 39b pass through the plates 38a, 38b and  
16 screw into the drive plates 36a, 36b, respectively, to compresses the ceramics 34. The  
17 transducers 32 are illustratively shown mounted to a tank surface 20'.

18  
19 The transducers 32a, 32b are driven by a common generator such as generator 12 of  
20 Figure 1. Alternatively, multiple generators can be used. The ceramics 34 are oriented with  
21 positive "+" orientations together or minus "-" orientations together to obtain cooperative  
22 expansion and contraction within each transducer 32. Lead-outs 42 illustrate the electrical  
23 connections which connect between the generator and the transducers 32 so as to apply a  
24 differential voltage there-across. The bolts 39a, 39b provide a conduction path between the  
25 bottoms 43 and tops 45 of the transducers 32 to connect the similar electrodes (here shown as  
26 -, -) of the elements 34.

27  
28 The thicknesses 40a, 40b of transducers 32a, 32b, respectively, determine the  
29 transducer's fundamental resonant frequency. For purposes of illustration, transducer 32a has

1 a fundamental frequency of 40khz, and transducer 32b has a fundamental frequency of  
2 44khz. Transducers 32a, 32b each have a finite ultrasound bandwidth which can be adjusted,  
3 slightly, by those skilled in the art. Typically, however, the bandwidths are about 4khz. By  
4 choosing the correct fundamental frequencies, therefore, an overlap between the bandwidths  
5 of the two transducers 32a, 32b can occur, thereby adding additional range within which to  
6 apply ultrasound 26a', 26b' to liquid 22'.

7  
8 The acoustic energy 26' applied to the liquid 22' by the combination of transducers  
9 32a, 32b is illustrated graphically in Figure 2A. In Figure 2A, the "x" axis represents  
10 frequency, and the "y" axis represents acoustical power. The outline 44 represents the  
11 bandwidth of transducer 32a, and outline 46 represents the bandwidth of transducer 32b.  
12 Together, they produce a combined bandwidth 43 which produces a relatively flat acoustical  
13 energy profile to the liquid 22', such as illustrated by profile 48. The flatness of the  
14 bandwidth 43 representing the acoustical profile 48 of the two transducers 32a, 32b is  
15 preferably within a factor of two of any other acoustical strength within the combined  
16 bandwidth 43. That is, if the FWHM defines the bandwidth 43; the non-uniformity in the  
17 profile 48 across the bandwidth 43 is typically better than this amount. In certain cases, the  
18 profile 48 between the two bandwidths 44 and 46 is substantially flat, such as illustrated in  
19 Figure 2A.

20  
21 The generator connected to lead-outs 42 drives the transducers 32a, 32b at frequencies  
22 within the bandwidth 43 to obtain broadband acoustical disturbances within the liquid 22'.  
23 As described herein, the manner in which these frequencies are varied to obtain the overall  
24 disturbance is important. Most preferably, the generator sweeps the frequencies through the  
25 overall bandwidth, and at the same time sweeps the rate at which those frequencies are  
26 changed. That is, one preferred generator of the invention has a "sweep rate" that sweeps  
27 through the frequencies within the bandwidth 43; and that sweep rate is itself varied as a  
28 function of time. In alternative embodiments of the invention, the sweep rate is varied

1 linearly, randomly, and as some other function of time to optimize the process conditions  
2 within the tank 20'.  
3

4 With further reference to Figures 1 and 1A, each of the elements 18 can have a  
5 representative bandwidth such as illustrated in Figure 2A. Accordingly, an even larger  
6 bandwidth 43 can be created with three or more transducers such as illustrated by transducers  
7 32a, 32b. In particular, any number of combined transducers can be used. Preferably, the  
8 bandwidths of all the combined transducers overlap to provide an integrated bandwidth such  
9 as profile 48 of Figure 2A. As such, each transducer making up the combined bandwidth  
10 should have a unique resonant frequency.  
11

12 Those skilled in the art understand that each of the transducers 18 and 32a, 32b,  
13 Figures 1 and 2A, respectively, have harmonic frequencies which occur at higher mechanical  
14 resonances of the primary resonant frequency. It is one preferred embodiment of the  
15 invention that such transducers operate at one of these harmonics, i.e., typically the first,  
16 second, third or fourth harmonic, so as to function in the frequency range of 100khz to  
17 350khz. This frequency range provides a more favorable environment for acoustic processes  
18 within the tanks 20, 20' as compared to low frequency disturbances less than 100khz. For  
19 example, ultrasound frequencies around the 40khz frequency can easily cause cavitation  
20 damage in the part 24. Further, such frequencies tend to create standing waves and other hot  
21 spots of spatial cavitation within the liquid.  
22

23 Accordingly, the benefits of applying a broadband acoustic disturbance to the liquid  
24 also apply to the 100-350khz microsonic frequencies. Similar to Figure 2A, Figure 2B  
25 illustrates a combined bandwidth 50 of harmonic frequencies in the range 100-350khz.  
26 Specifically, Figure 2B shows the combined bandwidth 50 that is formed by the bandwidth  
27 44' around the second harmonic of the 40Khz frequency, and the bandwidth 46' around the  
28 second harmonic of the 41.5khz frequency.  
29

1        Figure 3 shows in block diagram embodiment of a system 110 constructed according  
2 to the present invention. The system 110 includes a signal section 112 which drives a power  
3 module 121. The power module 121 powers the harmonic transducer array 122. The  
4 transducer array 122 are coupled to a liquid 123 by one of several conventional means so as  
5 to generate acoustic energy within the liquid 123. By way of example, the array 122 is similar  
6 to the array 16 of Figure 1; and the liquid 123 is similar to the liquid 22 of Figure 1.

7  
8        The signal section 112 includes a triangle wave oscillator 114 with a frequency  
9 typically below 150hz. The purpose of the oscillator 114 is to provide a signal that sweeps  
10 the sweep rate of the ultrasound frequencies generated by the transducer arrays 122.

11  
12        The oscillator 114 is fed into the input of the sweep rate VCO 115 (Voltage  
13 Controlled Oscillator). This causes the frequency of the output of VCO 115 to linearly sweep  
14 at the frequency of the oscillator 114. The optimum sweep rate frequency output of VCO  
15 115 is typically from about 10hz, for magnetostrictive elements, to about 1.2khz, for  
16 piezoelectrics. Therefore, the optimum center sweep rate frequency can be anywhere within  
17 the range of about 10hz to 1.2khz, and that sweep rate is varied within a finite range of  
18 frequencies about the center sweep frequency. This finite range is typically set to about 10-  
19 50% of the center sweep rate frequency. For example, the center sweep rate frequency for one  
20 process might be 455hz, so the VCO 115 output is set, for example, to sweep from 380hz to  
21 530hz. If, additionally, the oscillator 114 is set to 37hz, then the output of VCO 115 changes  
22 frequency, linearly, from 380hz to 530hz, and back to 380hz at thirty seven times per second.

23  
24        The output of VCO 115 feeds the VCO input of the 2 X center frequency VCO 116.  
25 The VCO 116 operates as follows. If, for example, the center frequency of VCO 116 is set to  
26 208khz and the bandwidth is set to 8khz, the center frequency linearly changes from 204khz  
27 to 212khz and back to 204khz in a time of 1.9 milliseconds (i.e.,  $1/530\text{hz}$ ) to 2.63  
28 milliseconds (i.e.,  $1/380\text{hz}$ ). The specific time is determined by the voltage output of the  
29 oscillator 114 at the time of measurement. Since the voltage output of oscillator 114 is



1 constantly changing, the time it takes to linearly sweep the center frequency from 204khz to  
2 212khz and back to 204khz is also constantly changing. In this example, the time changes  
3 linearly from 1.9ms to 2.63ms and back to 1.9ms at thirty seven times per second.

4  
5 The oscillator 114, VCO 115 and VCO 116 operate, in combination, to eliminate the  
6 repetition of a single sweep rate frequency in the range of 10hz to 1.2khz. For example, the  
7 highest single frequency that exists in the stated example system is 37hz. If an unusual  
8 application or process were found whereby a very low frequency resonance around 37hz  
9 exists, then the oscillator 114 would be replaced by a random voltage generator to reduce the  
10 liklihood of exciting any modes within the part.

11  
12 The VCO 116 drives a divide-by-two D flip-flop 117. The purpose of the D flip-flop  
13 117 is to eliminate asymmetries in the waveform from the VCO 116. The output of the D  
14 flip-flop 117 is thus a square wave that has the desired frequency which changes at a sweep  
15 rate that is itself sweeping. In the stated example, the output square wave from D flip-flop  
16 117 linearly changes from 102khz to 106khz and back to 102khz at different times in the  
17 range of 1.9ms to 2.63ms. This sweeping of the sweep rate is sometimes referred to herein as  
18 "double sweep" or "double sweeping."

19  
20 The AC line zero-crossover detection circuit 118 produces a signal with a rise time or  
21 narrow pulse at or near the time that the AC line voltage is at zero or at a low voltage, i.e., at  
22 or near zero degrees. This signal triggers the adjustable monostable multivibrator 119. The  
23 timed pulse out of monostable multivibrator 119 is set to a value between zero degrees and  
24 ninety degrees, which corresponds to a time from zero to 4.17ms for a 60hz line frequency.

25  
26 If the maximum amplitude were desired, for example, the monostable multivibrator  
27 119 is set to a time of 4.17ms for a 60hz line frequency. For an amplitude that is 50% of  
28 maximum, the monostable multivibrator 119 is set to 1.389ms for a 60hz line frequency. In

1 general, the monostable multivibrator 119 time is set to the arcsin of the amplitude percent  
2 times the period of the line frequency divided by 360 degrees.

3  
4 The double sweeping square wave output of the D flip-flop 117 and the timed pulse  
5 output of the monostable multivibrator 119 feed into the synchronization logic 120. The  
6 synchronization logic 120 performs three primary functions. First, it only allows the double  
7 sweeping square wave to pass to the output of the synchronization logic 120 during the time  
8 defined by the pulse from the monostable multivibrator 119. Second, the synchronization  
9 logic 20 always allows a double sweeping square wave which starts to be completed, even if  
10 the monostable multivibrator 19 times out in the middle of a double sweeping square wave.  
11 And lastly, the synchronization logic 120 always starts a double sweeping square wave at the  
12 beginning of the ultrasonic frequency, i.e., at zero degrees.

13  
14 The output of synchronization logic 120 is a double sweeping square wave that exists  
15 only during the time defined by the monostable multivibrator 119 or for a fraction of a cycle  
16 past the end of the monostable multivibrator 119 time period. The synchronization logic 120  
17 output feeds a power module 121 which amplifies the pulsed double sweeping square wave to  
18 an appropriate power level to drive the harmonic transducers 122. The transducers 122 are  
19 typically bonded to a tank and deliver sound waves into the liquid within the tank. These  
20 sound waves duplicate the pulsed double sweeping characteristics of the output of the signal  
21 section 112.

22  
23 Figure 4 shows a schematic embodiment of the signal section 112 in Figure 3. U1 is  
24 a XR-2209 precision oscillator with a triangle wave output at pin 8. The frequency of the  
25 XR-2209 is  $1/(RC) = 1/((27k)(1\mu f)) = 37hz$ . This sets the frequency of the triangle wave  
26 oscillator 114, Figure 3, to sweep the sweep rate at 37hz. The other components associated  
27 with the XR-2209 are the standard configuration for single supply operation of this integrated  
28 circuit.

1 U2 is a XR-2209 precision oscillator with a triangle wave output at pin8. The center  
2 frequency of U2 is  $1/(RC) = 1/((2.2k)(1\mu f)) = 455hz$ . The actual output frequency is  
3 proportional to the current flowing out of pin4 of U2. At 455hz, this current is  $6volts/2.2k =$   
4  $2.73ma$ . It is generally desirable, according to the invention, to sweep the 455hz sweep rate  
5 through a total change of 150hz, i.e., 75hz either side of 455hz. Since  $75hz/455hz = 16.5\%$ ,  
6 the current flowing out of pin 4 must change by 16.5% in each direction, that is, by  $(16.5\%)$   
7  $(2.73ma) = 0.45ma$ . The triangle wave from U1 causes this change. The triangle wave  
8 changes from 3volts to 9volts; therefore, there is 3volts on either side of 6volts at pin4 of U2  
9 to cause the 0.45ma change. By making  $R1 = 3volts/0.45ma = 6.67k\Omega$ , the sweep rate is  
10 changed 75hz either side of 455hz. The actual R1 used in Figure 4 is  $6.65k\Omega$ , a  
11 commercially available value giving an actual change of 75.2hz.

12  
13 U3 is a XR-2209 precision oscillator with a center frequency of approximately  $1/(RC)$   
14  $= 1/((12k + 2.5k)(330pf)) = 209khz$  with the potentiometer set to its center position of  
15  $2.5k\Omega$ . In the actual circuit, the potentiometer is adjusted to about  $100\Omega$  higher to give the  
16 desired 208khz center frequency. Out of U3 pin4 flows  $6volts/(12k\Omega + 2.5k\Omega + 100\Omega) =$   
17  $0.41ma$ . To change the center frequency a total of 8khz, the 0.41ma is changed by  
18  $4khz/208khz = 1.92\%$ , or  $7.88\mu a$ . This means that  $R2 = 3volts/7.88\mu a = 381k\Omega$ . In Figure 4,  
19 however, the commercial value of  $383k\Omega$  was used.

20  
21 U3 pin7 has a square wave output that is changing from 204khz to 212khz and back to  
22 204khz at a rate between 380hz and 530hz. The actual rate is constantly changing thirty  
23 seven times a second as determined by U1.

24  
25 U4 is a D flip-flop in a standard divide by two configuration. It squares up any non  
26 50% duty cycle from U3 and provides a frequency range of 102khz to 106khz from the  
27 204khz to 212khz U3 signal.

1       The output of U4 feeds the synchronization logic which is described below and after  
2 the description of the generation of the amplitude control signal.

3  
4       The two 1N4002 diodes in conjunction with the bridge rectifier form a full wave half  
5 sinusoid signal at the input to the 40106 Schmidt trigger inverter. This inverter triggers when  
6 the half sinusoid reaches about 7volts, which on a half sinusoid with an amplitude of 16 times  
7 the square root of two is close enough to the zero crossover for a trigger point in a practical  
8 circuit. The output of the 40106 Schmidt trigger falls which triggers U5, the edge triggered  
9 4538 monostable multivibrator wired in a trailing edge trigger/retriggerable configuration.  
10 The output of U5 goes high for a period determined by the setting on the 500k $\Omega$   
11 potentiometer. At the end of this period, the output of U5 goes low. The period is chosen by  
12 setting the 500k $\Omega$  potentiometer to select that portion of the leading one-quarter sinusoid that  
13 ends at the required amplitude to give amplitude control. This timed positive pulse feeds into  
14 the synchronization logic along with the square wave output of U4.

15  
16       The timed pulse U5 feeds the D input of U6, a 4013 D-type flip flop. The square  
17 wave from U4 is inverted by U7a and feeds the clock input of U6. U6 only transfers the  
18 signal on the D input to the output Q at the rise of a pulse on the clock input, Pin3.  
19 Therefore, the Q output of U6 on Pin1 is high when the D input of U6 on Pin3 is high and the  
20 clock input of U6 on Pin3 transitions high. This change in the Q output of U6 is therefore  
21 synchronized with the change in the square wave from U4.

22  
23       The synchronized high Q output of U6 feeds U8 Pin13, a 4093 Schmidt trigger  
24 NAND gate. The high level on Pin13 of U8 allows the square wave signal to pass from U8  
25 Pin12 to the output of U8 at Pin11.

26  
27       In a similar way, U8 synchronizes the falling output from U5 with the square wave  
28 from U4. Therefore, only complete square waves pass to U8 Pin11 and only during the time  
29 period as chosen by monostable multivibrator U5. The 4049 buffer driver U7b inverts the

1 output at U8 Pin11 so it has the same phase as the square wave output from U4. This signal,  
2 U7b Pin2 is now the proper signal to be amplified to drive the transducers.

3  
4 Figures 5A, 5B represent a circuit that increases the signal from U7b Pin 2 in Figure  
5 4 to a power level for driving the transducers 122, Figure 3. There are three isolated power  
6 supplies. The first one, including a T1, a bridge, C19, VR1 and C22, produces +12VDC for  
7 the input logic. The second and third isolated power supplies produce +15 VDC at VR2 Pin3  
8 and VR3 Pin3 for gate drive to the IGBT's (insulated gate bipolar transistors).

9  
10 The signal input to Figures 5A, 5B has its edges sharpened by the 40106 Schmidt  
11 trigger U9a. The output of U9a feeds the 4049 buffer drivers U10c and U10d which drive  
12 optical isolator and IGBT driver U12, a Hewlett Packard HCPL3120. Also, the output of  
13 U9a is inverted by U9b and feeds buffer drivers U10a and U10b which drive U11, another  
14 HCPL3120.

15  
16 This results in an isolated drive signal on the output of U11 and the same signal on the  
17 output of U12, only 180° out of phase. Therefore, U11 drives Q1 on while U12 drives Q2  
18 off. In this condition, a power half sinusoid of current flows from the high voltage full wave  
19 DC at B1 through D1 and Q1 and L1 into C1. Current cannot reverse because it is blocked  
20 by D1 and the off Q2. When the input signal changes state, U11 turns off Q1 and U12 turns  
21 on Q2, a half sinusoid of current flow out of C1 through L2 and D2 and Q2 back into C1 in  
22 the opposite polarity. This ends a complete cycle.

23  
24 The power signal across C1 couples through the high frequency isolation transformer  
25 T4. The output of T4 is connected to the transducer or transducer array.

26  
27 Figure 6 shows a cross-sectional side view of one clamped microsonic transducer 128  
28 constructed according to the invention; while Figure 6A shows a top view of the microsonic  
29 transducer 128. The microsonic transducer 128 has a second harmonic resonant frequency of

1 104khz with a 4khz bandwidth (i.e., from 102khz to 106khz). The cone-shaped backplate  
2 139 flattens the impedance verses frequency curve to broaden the frequency bandwidth of the  
3 microsonic transducer 128. Specifically, the backplate thickness along the "T" direction  
4 changes for translational positions along direction "X." Since the harmonic resonance of the  
5 microsonic transducer 128 changes as a function of backplate thickness, the conical plate 139  
6 broadens and flattens the microsonic transducer's operational bandwidth.

7  
8 The ceramic 134 of microsonic transducer 128 is driven through oscillatory voltages  
9 transmitted across the electrodes 136. The electrodes 136 connect to an ultrasonic generator  
10 (not shown), such as described above, by insulated electrical connections 138. The ceramic  
11 134 is held under compression through operation of the bolt 132. Specifically, the bolt 132  
12 provides 5,000 pounds of compressive force on the piezoelectric ceramic 134.

13  
14 Amplitude control according to one embodiment of the invention is illustrated in  
15 Figures 7 and 7A. Specifically, Figure 7 shows an amplitude control subsystem 140 that  
16 provides amplitude control by selecting a portion of the rectified line voltage 145 which  
17 drives the ultrasonic generator amplitude select section 146. The signal section 112, Figure 3,  
18 and particularly the monostable multivibrator 119 and synchronization logic 120, provide  
19 similar functionality. In Figure 7, the amplitude control subsystem 140 operates with the  
20 ultrasonic generator 142 and connects with the power line voltage 138. The rectification  
21 section 144 changes the ac to dc so as to provide the rectified signal 145.

22  
23 The amplitude select section 146 selects a portion of the leading quarter sinusoid of  
24 rectified signal 145 that ends at the desired amplitude, here shown as amplitude "A," in a  
25 region 148 between zero and 90° and in a region 150 between 180° and 270° of the signal  
26 145. In this manner, the amplitude modulation 152 is selectable in a controlled manner as  
27 applied to the signal 154 driving the transducers 156 from the generator 142, such as  
28 discussed in connection with Figures 3 and 4.

1        Figure 7A shows illustrative selections of amplitude control in accord with the  
2 invention. The AC line 158 is first converted to a full wave signal 160 by the rectifier 144.  
3 Thereafter, the amplitude select section 146 acquires the signal amplitude selectively. For  
4 example, by selecting the maximum amplitude of 90° in the first quarter sinusoid, and 270°  
5 in the third quarter sinusoid, a maximum amplitude signal 162 is provided. Similarly, a one-  
6 half amplitude signal 164 is generated by choosing the 30° and 210° locations of the same  
7 sinusoids. By way of a further example, a one-third amplitude signal 166 is generated by  
8 choosing 19.5° and 199.5°, respectively, of the same sinusoids.

9  
10        Those skilled in the art will appreciate that the rectification section 144 can also be a  
11 half-wave rectifier. As such, the signal 145 will only have a response every other one-half  
12 cycle. In this case, amplitude control is achieved by selecting a portion of the leading quarter  
13 sinusoid that ends at a selected amplitude between zero and 90° of the sinusoid.

14  
15        The ultrasonic generator of the invention is preferably amplitude modulated. Through  
16 AM control, various process characteristics within the tank can be optimized. The AM  
17 control can be implemented such as described in Figures 3,4,7 and 7A, or through other prior  
18 art techniques such as disclosed in U.S. Patent No. 4,736,130.

19  
20        This "sweeping" of the AM frequency is accomplished in a manner that is similar to  
21 ultrasonic generators which sweep the frequency within the bandwidth of an ultrasonic  
22 transducer. By way of example, U.S. Patent No. 4,736,130 describes one ultrasonic generator  
23 which provides variable selection of the AM frequency through sequential "power burst"  
24 generation and "quiet time" during a power train time. In accord with the invention, the AM  
25 frequency is changed to "sweep" the frequency in a pattern so as to provide an AM sweep  
26 rate pattern.

27  
28        Figure 8 illustrates an AM sweep subsystem 170 constructed according to the  
29 invention. The AM sweep subsystem 170 operates as part of, or in conjunction with, the

1 ultrasonic generator 172. The AM generator 174 provides an AM signal 175 with a  
2 selectable frequency. The increment/decrement section 176 commands the AM generator 174  
3 over command line 177 to change its frequency over a preselected time period so as to  
4 "sweep" the AM frequency in the output signal 178 which drives the transducers 180.

5  
6 U.S. Patent No. 4,736,130 describes one AM generator 56, Figure 1, that is suitable  
7 for use as the generator 174 of Figure 8. By way of example, Figure 8A illustrates one  
8 selectable AM frequency signal 182 formed through successive 500 $\mu$ s power bursts and  
9 300 $\mu$ s quiet times to generate a 1.25kHz signal (e.g.,  $1/(300\mu s + 500\mu s) = 1.25\text{kHz}$ ). If, for  
10 example, the AM frequency is swept at 500hz about a center frequency of 1.25kHz, such as  
11 shown in Figure 8, then the frequency is commanded to vary between 1.25kHz + 250hz and  
12 1.25kHz - 250hz, such as illustrated in Figure 8B. Figure 8B illustrates a graph of AM  
13 frequency versus time for this example.

14  
15 Figure 9 schematically illustrates a multi-generator, single tank system 200  
16 constructed according to the invention. In many instances, it is desirable to select an  
17 ultrasound frequency 201 that most closely achieves the cavitation implosion energy which  
18 cleans, but does not damage, the delicate part 202. In a single tank system such as in Figure  
19 9, the chemistries within the tank 210 are changed, from time to time, so that the desired or  
20 optimum ultrasound frequency changes. The transducers and generators of the prior art do  
21 not operate or function at all frequencies, so system 200 has multiple generators 206 and  
22 transducers 208 that provide different frequencies. By way of example, generator 206a can  
23 provide a 40kHz primary resonant frequency; while generator 206b can provide the first  
24 harmonic 72kHz frequency. Generator 206c can provide, for example, 104kHz microsonic  
25 operation. In the illustrated example, therefore, the generators 206a, 206b, 206c operate,  
26 respectively, at 40kHz, 72kHz, and 104kHz. Each transducer 208 responds at each of these  
27 frequencies so that, in tandem, the transducers generate ultrasound 201 at the same frequency  
28 to fill the tank 210 with the proper frequency for the particular chemistry.



1 In addition, each of the generators 206a-206c can and do preferably sweep the  
2 frequencies about the transducers' bandwidth centered about the frequencies 40khz, 72khz,  
3 and 104khz, respectively; and they further sweep the sweep rate within these bandwidths to  
4 reduce or eliminate resonances which might occur at the optimum sweep rate.

5  
6 When the tank 210 is filled with a new chemistry, the operator selects the optimum  
7 frequency through the mux select section 212. The mux select section connects to the analog  
8 multiplexer ("mux") 214 which connects to each generator 206. Specifically, each generator  
9 206 couples through the mux 214 in a switching network that permits only one active signal  
10 line 216 to the transducers 208. For example, if the operator at mux select section 212  
11 chooses microsonic operation to optimize the particular chemistry in the tank 210, generator  
12 206c is connected through the mux 214 and drives each transducer 208a-208c to generate  
13 microsonic ultrasound 201 which fills the tank 210. If, however, generator 206a is selected,  
14 then each of the transducers 208 are driven with 40khz ultrasound.

15  
16 Figure 9A illustrates another single tank, multi-generator system 200' constructed  
17 according to the invention. Specifically, like in Figure 9, each of the generators 206' provides  
18 a different frequency. However, each generator 206' connects to drive unique transducer  
19 arrays 208' within the tank 210'. In this manner, for example, generator 206a' is selected to  
20 generate 40khz ultrasound 201a in the tank 210'; generator 206b' is selected to generate  
21 72khz ultrasound 201b in the tank 210'; and generator 206c is selected to generate 104khz  
22 microsonics 201c in the tank 210'. These generator/transducer pairs 206a'/208a',  
23 206b'/208b' and 206c'/208c' do not generally operate at the same time; but rather are  
24 selected according to the process chemistries and part 202' in the tank 210'.

25  
26 Those skilled in the art should appreciate that each of the generators 206 can be  
27 replaced by multiple generators operating at the same or similar frequency. This is sometimes  
28 needed to provide additional power to the tank 210 at the desired frequency. Those skilled in

1 the art should also appreciate that the mux 214 can be designed in several known methods,  
2 and that techniques to do so abound in the art.

3  
4 Figure 10 illustrates a multi-generator, common frequency ultrasound system 230  
5 constructed according to the invention. In Figure 10, a plurality of generators 232 (232a-  
6 232c) connect through signal lines 234 (234a-234c) to drive associated transducers 238  
7 (238a-238c) in a common tank 236. Each of the transducers 238 and generators 232 operate  
8 at the same frequency, and are preferably swept through a range of frequencies such as  
9 described above so as to reduce or eliminate resonances within the tank 236 (and within the  
10 part 242).

11  
12 In order to eliminate "beating" between ultrasound energies 240a-240c of the the  
13 several transducers 238a-238c and generators 232a-232c, the generators 232 are each driven  
14 by a common FM signal 250 such as generated by the master signal generator 244. The FM  
15 signal is coupled to each generator through signal divider 251.

16  
17 In operation, system 230 permits the coupling of identical frequencies, in magnitude  
18 and phase, into the tank 236 by the several transducers 238. Accordingly, unwanted beating  
19 effects are eliminated. The signal 250 is swept with FM control through the desired  
20 ultrasound bandwidth of the several transducers to eliminate resonances within the tank 236;  
21 and that sweep rate frequency is preferably swept to eliminate any low frequency resonances  
22 which can result from the primary sweep frequency.

23  
24 Those skilled in the art should appreciate that system 230 of Figure 10 can  
25 additionally include or employ other features such as described herein, such as AM  
26 modulation and sweep, AM control, and broadband transducer.

27  
28 Figure 11 illustrates a multi-tank system 260 constructed according to the invention.  
29 One or more generators 262 drive each tank 264 (here illustrated, generators 262a and 262b

1 drive tank 264a; and generators 264c and 264d drive tank 264b). Each of the generators 262  
2 connects to an associated ultrasound transducer 266a-d so as to produce ultrasound 268a-d in  
3 the associated tanks 264a-b.

4  
5 The common master signal generator 270 provides a common FM signal 272 for each  
6 of the generators 262. Thereafter, ultrasound generators 262a-b generate ultrasound 268a-b  
7 that is identical in magnitude and phase, such as described above. Similarly, generators 262c-  
8 d generate ultrasound 268c-d that is identical in magnitude and phase. However, unlike  
9 above, the generators 262 each have an AM generator 274 that functions as part of the  
10 generator 262 so as to select an optimum AM frequency within the tanks 264. In addition, the  
11 AM generators 274 preferably sweep through the AM frequencies so as to eliminate  
12 resonances at the AM frequency.

13  
14 More particularly, generators 274a-b generate and/or sweep through identical  
15 frequencies of the AM in tank 264a; while generators 274c-d generate and/or sweep through  
16 identical frequencies of AM in tank 264b. However, the AM frequency and/or AM sweep of  
17 the paired generators 274a-b need not be the same as the AM frequency and/or AM sweep of  
18 the paired generators 274c-d. Each of the generators 274 operate at the same carrier  
19 frequency as determined by the FM signal 270; however each paired generator set 274a-b and  
20 274c-d operates independently from the other set so as to create the desired process  
21 characteristics within the associated tank 264.

22  
23 Accordingly, the system 260 eliminates or prevents undesirable cross-talk or  
24 resonances between the two tanks 264a-b. Since the generators within all tanks 264 operate  
25 at the same signal frequency 270, there is no effective beating between tanks which could  
26 upset or destroy the desired cleaning and/or processing characteristics within the tanks 264.  
27 As such, the system 260 reduces the likelihood of creating damaging resonances within the  
28 parts 280a-b. It is apparent to those skilled in the art that the FM control 270 can contain the  
29 four AM controls 274a-d instead of the illustrated configuration.

1  
2 Figure 11A shows two AM patterns 300a, 300b that illustrate ultrasound delivered to  
3 multiple tanks such as shown in Figure 11. For example, AM pattern 300a represents the  
4 ultrasound 268a of Figure 11; while AM pattern 300b represents the ultrasound 268c of  
5 Figure 11. With a common FM carrier 302, as provided by the master generator 270, Figure  
6 11, the ultrasound frequencies 302 can be synchronized so as to eliminate beating between  
7 tanks 264a, 264b. Further, the separate AM generators 274a and 274c provide capability so  
8 as to select the magnitude of the AM frequency shown by the envelope waveform 306. As  
9 illustrated, for example, waveform 306a has a different magnitude 308 as compared to the  
10 magnitude 310 of waveform 306b. Further, generators 374a, 374c can change the periods  
11 310a, 310b, respectively, of each of the waveforms 306a, 306b selectively so as to change the  
12 AM frequency within each tank.

13  
14 Figures 12A, 12B and 12C graphically illustrate the methods of sweeping the sweep  
15 rate, in accord with the invention. In particular, Figure 12A shows an illustrative condition of  
16 a waveform 350 that has a center frequency of 40khz and that is varied about the center  
17 frequency so as to "sweep" the frequency as a function of time along the time axis 352.  
18 Figure 12B illustrates FM control of the waveform 354 which has a varying period 356  
19 specified in terms of time. For example, a 42khz period occurs in 23.8 $\mu$ s while a 40khz  
20 period occurs in 25 $\mu$ s. The regions 358a, 358b are shown for ease of illustration and  
21 represent, respectively, compressed periods of time within which the system sweeps the  
22 waveform 354 through many frequencies from 42khz to 40khz, and through many  
23 frequencies from 40khz to 38khz.

24  
25 Figure 12c graphically shows a triangle pattern 360 which illustrates the variation of  
26 sweep rate frequency along a time axis 362.

27  
28 The invention thus attains the objects set forth above, among those apparent from  
29 preceding description. Since certain changes may be made in the above apparatus and

1 methods without departing from the scope of the invention, it is intended that all matter  
2 contained in the above description or shown in the accompanying drawing be interpreted as  
3 illustrative and not in a limiting sense.

4  
5 It is also to be understood that the following claims are to cover all generic and  
6 specific features of the invention described herein, and all statements of the scope of the  
7 invention which, as a matter of language, might be said to fall there between.

8  
9 Having described the invention, what is claimed as new and secured by Letters Patent  
10 is: